Naval Command,
Control and Ocean
Surveillance Center RDT&E Division

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Improved Operator Awareness of Teleoperated Land Vehicle Attitude

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

OBJECTIVE

The operator of a teleoperated land vehicle must have a sufficient understanding of the remote vehicle attitude to successfully operate it in an unstructured outdoor environment. The goal of this effort was to develop a human–machine interface that provides sufficient remote vehicle attitude information while minimally impacting operator workload.

APPROACH

The approach began with a study of the human orientation system, specifically sensor stimulation and anatomic sensor data processing. Potential methods for presenting vehicle attitude information to the operator that stimulate the human orientation system were identified and explored.

The method of gravity-referencing the remote sensor package was implemented. This method involved referencing the remote visual sensors to the gravitational field of the earth. The hood of the remote vehicle appeared in the video image transmitted to the control station and provided the operator with vehicle pitch and roll information. The effectiveness of this method versus vehicle-referencing the sensors was experimentally investigated.

RESULTS AND RECOMMENDATIONS

Statistically significant improvement (with a 99.9 percent confidence level) was observed in the operator's understanding of remote vehicle attitude, both pitch and roll, when the sensor package was gravity-referenced compared with when it was vehicle-referenced.

The improvement in the operator's understanding of the vehicle roll angle with gravity-referenced sensors was greater than that for the pitch angle and was operationally significant. To enhance the effectiveness of the gravity-referencing method for pitch angle estimation, a simple graphic indicator could be overlaid on the edge of the video display, providing angular position meaning to the linear movement of the vehicle hood in the video image. Although the graphical indicator was not formally tested, informal investigation indicated that the gravity-referencing method coupled with the simple graphical indicator would provide an operationally significant improvement in pitch angle understanding.

Experimental results showed a significantly higher level of operator confidence in vehicle attitude awareness with the gravity-referencing method. A minimal increase in operator workload was also documented for the method of gravity-referencing.

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1. INTRODUCTION

Teleoperation is the manipulation of a remote system from a controller site. The motivation behind it is simple—to remove the human worker from an inconvenient, dangerous, or unreachable work site while retaining control and decision-making capabilities over a situation.

1.1 TELEOPERATED LAND VEHICLES

Much of the modern battlefield, with smart weapons and nuclear–biological–chemical (NBC) munitions, is becoming too hostile for humans to survive and contribute to the outcome of the conflict [Shaker and Wise, 1988]. The Department of Defense (DoD) has realized the need to replace soldiers engaged in missions or located in environments with little survivability and is investing in programs to develop robotic systems for high-risk or hostile battlefield applications [Aviles et al., 1990; DoD, 1991].

Robotic vehicles can be autonomous with remote vehicle intelligence, semi-autonomous with intermittent teleoperated control, or teleoperated with little remote vehicle intelligence. Both teleoperated and autonomous systems have strong points and limitations that make them suitable for different battlefield missions.

Teleoperation allows the military command to have complete and continuous control over vehicle actions and movement. Thus, the system is robust and adaptive in an unstructured environment or unforeseen scenario. Responses of force are initiated and controlled by a human operator; therefore, there need not be any concern of a machine inappropriately directing force. The communications link between the vehicle and operator is vulnerable to breakage or jamming; if the link becomes nonfunctional, the system is useless. Teleoperated vehicles would be suitable for reconnaissance, surveillance, and target acquisition missions immediately ahead of troops. With current communication link configurations, the teleoperated system would not be effective for deep penetration behind enemy lines. Autonomous systems are better suited for that type of mission. Both autonomous and teleoperated vehicles could be used to draw fire away from troops. [Shaker and Wise, 1988]

Although the development of teleoperated land vehicles has been focused on military applications, unmanned land vehicles are beginning to, or may soon, find a place in space exploration, drug enforcement, border patrol, and security surveillance activities [Courtright, 1991].

1.2 REMOTE VEHICLE ATTITUDE AWARENESS

One of the critical technology areas in teleoperated land vehicle development is the human–machine interface [DoD, 1991]. A key issue in the human–machine interface design is the operator's insufficient understanding of the remote vehicle attitude [Aviles et al., 1990]. This lack of awareness is a roadblock for the safe and effective operation of teleoperated ground vehicles over rough terrain and in off-road situations. Teleoperated vehicle roll-over accidents, attributable to insufficient vehicle attitude cues being presented to the operator, have been documented by Sandia National Laboratories [McGovern, 1990]. Also, the Naval Command, Control, and Ocean Surveillance Center's Research, Development, Test, and Evaluation Division (NCCOSC RDT&E) has witnessed and documented near roll-over incidents due to insufficient vehicle attitude awareness [Aviles et al., 1990].

A teleoperated vehicle operator extracts remote vehicle attitude cues from a video display; in addition, some teleoperator control consoles are equipped with a vehicle pitch and roll indicator. This configuration does not supply sufficient cues for the operator to understand and react to the continuously changing attitude of the remote vehicle as it traverses rough terrain [Aviles et al., 1990].

1.3 OBJECTIVE

The goal of this effort was to develop a human–machine interface that provides remote vehicle attitude information, sufficient for the successful teleoperation of the system, while minimally impacting operator workload.

This report begins with a review of the human orientation system, specifically sensor stimulation and anatomic sensor data processing. Much of the literature in this area is from the aviation medical community. Potential methods for presenting vehicle attitude information to the operator that stimulate the human orientation system are identified and explored.

Next, the selected method is discussed. This method involved referencing the remote visual sensors to the gravitational field of the earth. The hood of the remote vehicle appeared in the video image transmitted to the control station and provided the operator with vehicle pitch and roll information. A two-degree-of-freedom platform for referencing the cameras was designed and prototyped. The system responded only to changes in terrain slope and ignored transient bumps, so that information about terrain roughness was not lost.

The prototype hardware was integrated on a teleoperated ground vehicle test bed. The effectiveness of gravity-referencing the remote sensors was experimentally investigated. Results are presented and reviewed.

Finally, suggestions are offered for the implementation of the gravity-referencing method on teleoperated land vehicle systems.

2. PRELIMINARY INVESTIGATIONS

The first step was to study the human sensory system, which provides orientation information. When an operator is directly driving a vehicle, the human body collects and processes orientation data. This information enables the operator to understand the orientation of the vehicle. When the operator is teleoperating a vehicle, orientation cues must be recreated or artificial cues generated at the control console for the operator to sufficiently understand the attitude of the remote vehicle.

2.1 HUMAN ORIENTATION SYSTEM

The collection and, in some cases, processing of orientation information are carried out by the visual, vestibular and nonvestibular proprioceptors, mechanoreceptors, and auditory subsystems.

Vision has been identified as the most important subsystem in spatial orientation awareness [Gillingham and Wolfe, 1986]. The anatomic sensors associated with vision are cones and rods. Cones are responsible for sharp visual acuity and color vision; rods provide less visual discrimination but are more sensitive to low light levels. The visual subsystem is composed of two separate and independent systems, with distinct principal functions.

Peripheral, or ambient, vision is predominately responsible for spatial orientation. Both rods and cones provide the sensor basis for peripheral vision.

Foveal, or focal, vision is involved with object recognition. Although not primarily responsible for spatial orientation, foveal vision is used, at times, to gather cues about orientation, e.g., an airplane pilot viewing pitch, roll, and yaw instruments. In this employment of foveal vision, a learned complex cognitive process is required to translate the collected data into usable orientation information. The sensor foundation for focal vision is the fovea centralis, the highest density area of cones located near the posterior pole of the eye [Gillingham and Wolfe, op. cit.].

The vestibular system detects accelerations of the body and processes the data into orientation information. This information is then employed for vision stabilization and for the execution of voluntary and reflexive motion. In the absence of vision, vestibular cues can usually provide a reasonable picture of one's position and orientation [Gillingham and Wolfe, op. cit.].

Nonvestibular proprioceptors include the muscle, tendon, and joint sensors. Like the vestibular system, they are sensitive to accelerations. The information they collect is integrated with the vestibular proprioceptor information [Gillingham and Wolfe, op. cit.].

Mechanoreceptors are pressure-sensitive sensors in the skin. The information they gather is also combined with that of the vestibular system [Gillingham and Wolfe, op. cit.].

The binaural auditory subsystem utilizes magnitude, phase, and arrival time differences to localize a sound source. Also, a rotating sound from a stationary source can be detected and translated into a rotating motion of the body. In addition, one can interpret specific sounds to have meaning, e.g., an audio warning alarm on an instrument panel, but this requires a learned complex cognitive process.

2.2 ORIENTATION CUES FOR TELEOPERATION

After obtaining a basic understanding of the human orientation system, the second step in the effort was to identify methods of presenting remote vehicle attitude data in such a manner as to

stimulate the operator's orientation sensors. For the purpose of this effort, the human subsystems were grouped into three categories: visual, proprioceptors (vestibular and non-vestibular) and mechanoreceptors, and auditory. Methods of presenting orientation cues were identified, then classified as a stimulant of one of the three categories of human orientation subsystems. Potential methods are listed in table 2.1.

Table 2-1. Potential methods for vehicle attitude feedback.

Vision	Proprioceptors, Mechanoreceptors	Audio
Stereo display	Motion seat	Binaural display
Color display	Force reflective vehicle controls	Warning and alarm sounds
Wide field-of-view display		
Gravity-referenced vision sensors		
Numeric or graphic attitude indicator		

Video gravity-referencing was selected as the initial method to be further investigated to determine its effectiveness in providing remote vehicle attitude information to the operator. This selection does not dismiss the other methods; the research had to begin by prototyping and testing one "good candidate" method. This method stimulates the operator's peripheral vision subsystem, requires no changes to a control console equipped with a video display, and requires no additional communication channels between the remote vehicle and the control site.

3. PROTOTYPE PLATFORM DESIGN

A prototype gravity-referencing platform was developed and integrated on a teleoperator test bed at NCCOSC RDT&E, Kaneohe Detachment. The test vehicle was a High Mobility Multi-Purpose Wheeled Vehicle (HMMWV), equipped with color, stereo vision, and binaural audio sensors. The sensors were mounted on the referencing platform. The platform was located in the area between the traditional driver's and passenger's seats. Sensors were mounted at an elevation equal to the average height of the eyes and ears of a 6-foot-tall human in the driving position [Diffrient, Tilley, and Bardagjy, 1974].

The hood of the remote vehicle appeared in the video image and served as an artificial horizon indicator, providing the operator with vehicle pitch and roll information. The cameras were positioned so that the hood of the vehicle filled the lower one-third of the video frame when the vehicle was on level terrain. The platform did not stabilize the remote sensors; it responded to changes in terrain slope but not to transient bumps. A stabilization scheme would forfeit information on road roughness.

3.1 REQUIREMENTS

A two-degree-of-freedom-actuated platform was designed to gravity-reference the remote vision sensors. The design was subject to the performance, operational, and physical requirements described in the following three sections.

3.1.1 Performance

The platform was implemented on an HMMWV. The vehicle was capable of transiting 60-percent pitch axis grades ($\sim$30 degrees) and 40-percent roll axis grades ($\sim$20 degrees). To effectively gravity-reference the remote sensor package, the platform must be capable of the same range of motion as the vehicle, $\pm$30 degrees (0.52 radian) pitch and $\pm$20 degrees (0.35 radian) roll.

The aggregate system accuracy specification for angular positioning was determined by considering the accuracy of candidate position sensors and the accuracy required for testing purposes. The figure arrived at was $\pm$1.5 degrees (0.026 radian), which is both reasonable to implement in hardware and sufficient for testing vehicle attitude awareness.

The slew rate for the prototype platform was determined by considering the test scenario and terrain used for data collection. An HMMWV equipped with a rate sensor was driven over rough, off-road terrain at 20 to 25 mph. The maximum rate of change of the terrain recorded was 60 deg/s. The test data were to be collected at an average vehicle speed of 7 mph. Therefore, a platform slew rate of 20 deg/s (0.35 rad/s) should be sufficient to track the maximum rate of change of the representative terrain.

The duty cycle for each actuator was developed in conjunction with the motor selection. The specified duty cycle accommodated the slew rate requirement for angle changes as small as 1.4 degrees, i.e., it would take 0.07 second for the actuator to move 1.4 degrees. The acceleration required was 1146 deg/s^2 (20.0 rad/s^2).

The sensors used to detect angular position of the vehicle must have a linear output over the range of motion required of the platform. Also, the update rate of the sensor must be at least twice the frequency of the terrain (> 2•20 hertz = 40 hertz).

The prototype platform must operate within performance guidelines with the vision and auditory sensor package load.

3.1.2 Operational

Test data were to be collected at Bellows Air Force Station in Waimanalo, Hawaii, over dirt roads and HMMWV-blazed terrain (the details are described in Section 4.2, Data Collection and Processing). The platform and the data collection instrumentation would be required to operate continuously for up to 6 hours, with a maximum air temperature of 95°F and a vehicle surface temperature (for hardware mounts) of 110°F. In addition, the hardware would be subjected to a rough ride and very dusty conditions.

The platform had to be easy to calibrate and manually control in the field. The alternation between gravity- and vehicle-referencing techniques needed to be simple and quick.

3.1.3 Physical

The platform developed was a prototype; it was installed on an existing HMMWV vehicle that was used for teleoperator development. As a result, the platform would be subjected to some physical size requirements so that it could be mounted in the available space and still operate effectively for the assigned task.

3.2 HARDWARE

The physical size constraint for the platform was the major factor that led to the design illustrated in figure 3-1. The actuators, located directly under the rotating plate, used a linear "pushing" action to achieve the required angular range of motion.

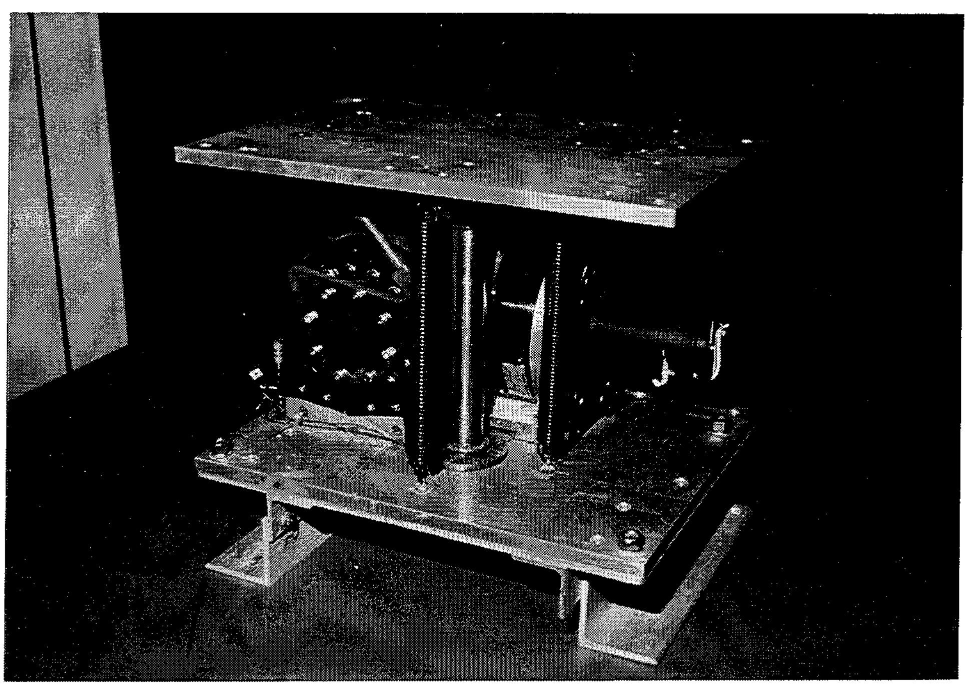

Figure 3-1. Two-degree-of-freedom platform, front view.

The platform was constructed from aluminum, except for the push-rods, cams, universal joints, and primary support post; these were constructed from steel, for strength. Mechanical springs were positioned on each axis to reduce the lateral motion introduced into the system by the push rod and cam connection. Limit switches were mounted in the path of the rotating cam, on either side of the actuator base. The switches prevented rotational movement in excess of the platform's physical limits.

Each axis was actuated by a dc motor coupled with a harmonic gear head. The motor and gear head combination was selected to meet the load and performance requirements. A two-degree-of-freedom inclinometer was used for pitch and roll detection. The unit integrated the velocity data from a solid-state angular rate sensor for fast angular position updates. In addition, it had a pendulum sensor that was used to recalibrate the integrated rate sensor data every 60 seconds. This coupled design afforded fast and accurate angular position information. The update rate of the sensor was 55 hertz. The sensor had a linear angular position output range of ± 30 degrees, with an accuracy rating of less than ± 0.9 degree. The rate sensor component saturated at a frequency of 100 deg/s.

3.3 CONTROL

A control algorithm was developed to calculate the torque necessary to move each joint from its present position to a new position along a specified trajectory. The designed closed-loop proportional-differential cascade control algorithm satisfied the performance requirements for the platform.

The control strategy was implemented in analog electronics. The actuators and controller operated on 24 volts supplied from two 12-volt lead-acid batteries wired in series. The power requirement was 7 amps at 24 volts.

The control electronics were designed to accept voltage inputs from two angular-position sensors or from two hand-turned potentiometers. Each axis had a select switch for the input source. This configuration provided for efficient switching between gravity- and vehicle-referencing methods and for quick field calibration.

4. EFFECTIVENESS OF GRAVITY-REFERENCING

A full-factorial experiment was conducted to compare the effectiveness of a teleoperator system with gravity-referenced sensors to the same teleoperator system with vehicle-referenced sensors (i.e., sensors fixed relative to the vehicle and subject to the same motion). The test subject's error in estimating the pitch and roll angles was the parametric used to measure the effectiveness of the methods.

4.1 EXPERIMENTAL DESIGN

The experiment was designed to emulate a typical remote vehicle driving scenario in an unstructured environment. This scenario was to be a dynamic situation requiring an on-the-fly operator response: *The vehicle is being teleoperated over rough, unfamiliar terrain. The operator must continually be aware of the vehicle attitude to determine if continued operation is safe, whether to reduce or increase speed, and if an alternative route must be pursued.*

For cost and safety reasons, the experiment was conducted in the laboratory using field-collected data.

4.2 DATA COLLECTION AND PROCESSING

The HMMWV was taken to Bellows Air Force Station and driven over rough dirt roads and HMMWV-blazed terrain. Stereo, color video, binaural audio, and vehicle pitch and roll data were collected. Driving courses were traversed twice at a speed of 7 $\pm$ 3 mph, alternating between gravity-referencing the sensors and vehicle-referencing the sensors. Figure 4.1 shows the data-collection instrumentation.

Stereo video was recorded on Recorder 1 using a field sequential mixer. Monocular video was recorded directly on Recorder 2. The binaural audio was recorded on the audio tracks of Recorder 1. The pitch and roll data were measured with the same model of inclinometer used on the two-degree-of-freedom platform described in Section 3.2, Hardware. The voltage signals were converted to corresponding frequencies, then recorded on the two audio tracks of Recorder 2. A clapboard was used at the begining of each clip so that the video signals on Recorder 1 and Recorder 2 could be synchronized during the editing process.

The data were edited into clips and transferred to two optical disks, one for gravity- and the other for vehicle-referenced data. The optical disk medium was chosen to enable the random selection and playback of the clips during testing.

4.3 EXPERIMENTAL PROCEDURE

Each test subject received an introductory brief, both verbal and written; the written explanation is included in the Appendix. Also, every subject signed a voluntary consent form and completed a pretest questionnaire (details are presented in Section 4.4, Test Subjects). After each test session, the subjects were asked to complete a posttest questionnaire. Both questionnaires are included in the Appendix.

Each subject participated in two practice sessions followed by two 20-minute test sessions. Each of the two test sessions (as well as the practice sessions) featured a different method—gravity- or vehicle-referencing—of presenting remote vehicle attitude information

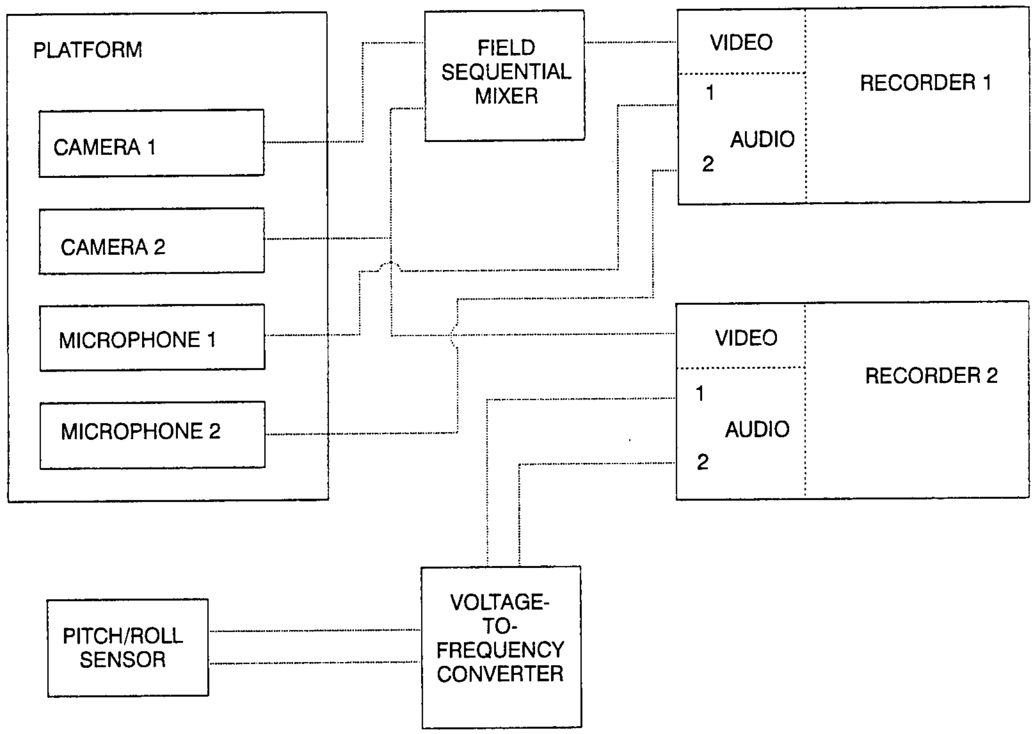

Figure 4-1. Field data-collection instrumentation.

via video and audio displays. Each test session consisted of 14 driving scenarios, 45 seconds in length. At three random points during each 45-second scenario, the video and audio stopped and the test subject made an estimate of the HMMWV pitch and roll angles. The test subject expressed estimates by positioning a gimballed model vehicle (see figure 4-2) in the same spatial orientation as the observed HMMWV.

Testing was conducted in the laboratory, as shown in figure 4-3. The test subject was seated at a distance behind a 21-inch color monitor to match the 39-degree horizontal field-of-view at which the video was collected. The subject wore flicker glasses (for field sequential stereo viewing) and stereo headphones (for binaural hearing). The subject positioned the model vehicle with one or both hands, whichever was easier and more comfortable. When the vehicle was positioned, the subject depressed a hand-held switch, and a pitch and roll reading was taken of the orientation of the model vehicle.

The randomized experimental design was implemented with control software developed on a MacIntosh IIfx using National Instruments Labview II programming environment. The gravity-referenced driving scenario clips were stored on one optical disk and the vehicle-referenced clips were stored on another. The clips were called up and presented to the test subject in a random, but continuous fashion. The gravity-referenced clips were shown first to alternate subjects; the other subjects were shown the vehicle-referenced clips first. Estimated pitch and roll data were collected via an analog-to-digital computer board and converted from a voltage to a corresponding angle measurement. Actual pitch and roll data were extracted from the audio tracks, converted from a frequency to a corresponding voltage, and were stored in an input data file. Test instrumentation is diagramed in figure 4-4.

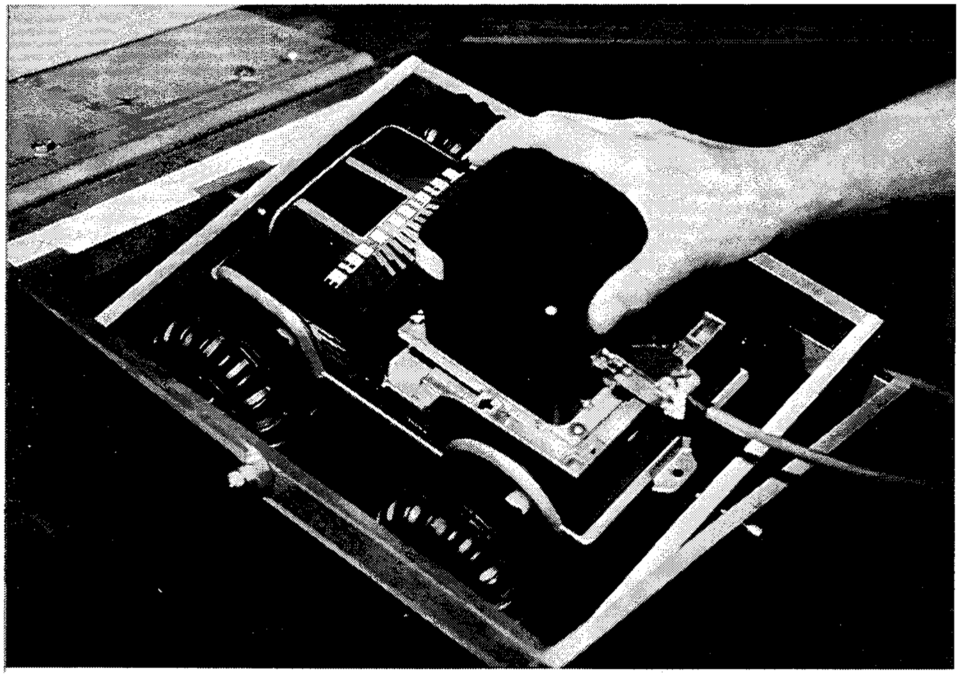

Figure 4-2. Gimballed model vehicle used to input estimates of pitch and roll angles.

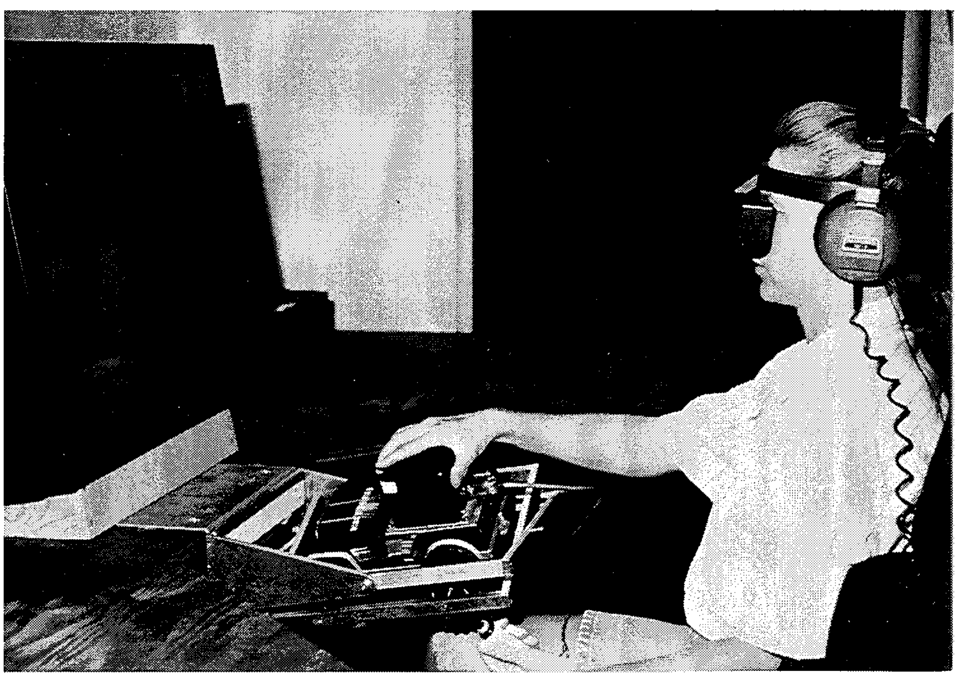

Figure 4-3. Test operator's station.

Figure 4-3. Test operator's station.

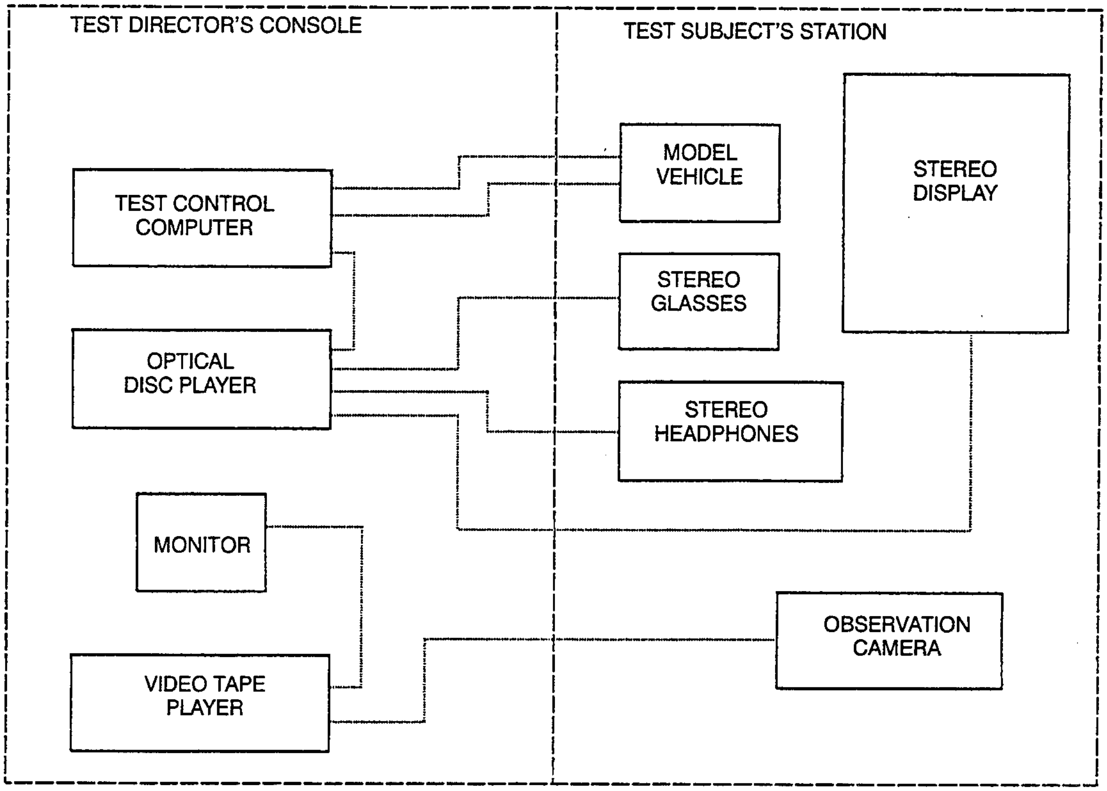

Figure 4-4. Experiment instrumentation.

4.4 TEST SUBJECTS

The 12 test subjects were recruited, on a voluntary basis, from NCCOSC RDT&E, Kaneohe Detachment, and the University of Hawaii at Manoa. None of the test subjects were familiar with the effort. Since orientation feedback stimuli for the experiment were to be presented in stereo video and binaural audio formats, the subject candidates were screened for uncorrected vision and hearing problems and also for difficulties with stereoscopic vision.

A pretest questionnaire was administered to characterize the subject pool. The information is introduced in table 4-1.

4.5 EXPERIMENTAL ANALYSIS

Each test subject generated 42 angle estimation data points for each of the two test sessions, for a total sample size of 1008 data points. Additional information collected for each data point included subject identification number, test session number, referencing method, and, of course, actual angle data.

As stated earlier, the test subject's error in estimating the pitch and roll angles was the parametric used to measure the effectiveness of the methods. Methods of statistical inference were employed to show that the variance in the angle-estimation errors was attributable to the referencing method and not just random, or chance, variation.

Table 4-1. Test operator characteristics.

Subject ID No.	Occupation	No. Years as Licensed Driver	Suscep-tibility to Motion Sickness	HMMWV Experience	Off-Road Driving Experience as Driver
1	Student	8	Moderate	Observer	None
2	Administrative Assistant	8	Moderate	Observer	None
3	Engineer	18	Moderate	Driver	Minimal
4	Engineer	30	Moderate	Driver	Minimal
5	Engineer	14	Minimal	Driver	Minimal
6	Engineer	29	Minimal	Observer	Substantial
7	Engineer	12	Minimal	Observer	Minimal
8	Administrative Assistant	21	High	Observer	Minimal
9	Financial Specialist	16	Minimal	Observer	None
10	Computer Scientist	14	Minimal	Observer	Moderate
11	Mechanical Technician	40	Nonexistent	Driver	None
12	Student	19	Minimal	Observer	None

The null hypothesis (H_0) developed for this study is that *there are no differences between the values of angle estimation error (the dependent variable) that can be explained by differences in sensor referencing techniques, test operators, or test session order (the independent variables, or treatments).*

An analysis of variance (ANOVA) was done on the collected data. ANOVA is a technique for identifying the sources of variation that contribute to the total variation of a data set. It is a tool for testing the null hypothesis against a collection of alternative hypotheses.

When significant differences are observed in the values of the dependent variable that are attributable to independent variables, the null hypothesis is rejected. If no significant differences are discovered, the null hypothesis is not proven true, but is tentatively accepted.

The ANOVA test partitions the total sample variance into the "between" treatment variance, or treatment mean sum of squares (MSTr), and the "within" treatment variance, or error mean sum of squares (MSE). The between treatment MSTr represents the variance due to the effectiveness of the treatments and the within MSE expresses the variance due to chance. The ratio of MSTr to MSE produces a variable which follows the F-distribution [Huntsberger, 1967; Miller and Freund, 1977]. The ANOVA uses the observed F-value to decide on the rejection of the null hypothesis. The observed F-value is compared with the theoretical F-value. The probability that an F-value as large as the observed F-value could occur by chance (if the null hypothesis is not rejected) is calculated. A typical cutoff level employed for reporting statistically significant differences (i.e., rejecting H_0) is 0.05 [Gagnon et al., 1989]; this means that only 5 percent of the time, H_0 would be incorrectly rejected.

Since implementing a rejection of the null hypothesis for this experiment could mean a hardware change to teleoperated vehicles, a stricter cutoff level of 0.01 was adopted for the rejection of H_0. This means that only 1 percent of the time H_0 would be incorrectly rejected.

The primary null hypothesis was investigated, and each subject's vehicle attitude awareness in the critical ranges (i.e., pitch and roll angles exceeding 10 degrees) was evaluated. On the posttest questionnaire, subjects were asked to rate their level of confidence regarding their estimates and to rate the task workload of making estimates for the two methods. These results are also reported.

4.6 EXPERIMENTAL RESULTS

Vehicle pitch and roll estimation errors were investigated separately. ANOVAs were conducted with roll and pitch estimation errors as the dependent variables and the subject identification number, test session number, and referencing method as independent effects.

4.6.1 Learning and Order Effect

The 12 test subjects were each assigned a number. The odd-numbered subjects were first tested on the gravity-referencing method and then on the vehicle-referencing method. The order of testing was reversed for the even-numbered subjects. This was done to reduce any effects of order and learning. Results of the ANOVAs—table 4.2 for roll estimation and table 4.3 for pitch estimation—confirmed that differences in angle estimation errors were not attributable to test session order.

Table 4-2. ANOVA for roll estimation error.

Source	Degree-of-Freedom	Sum of Squares	Mean Square	*F*-Value	*p*-Value
Reference Method	1	3512.693	3512.693	206.590	0.0001
Subject ID	11	971.065	88.279	5.192	0.0001
Session	1	31.609	31.609	1.859	0.1730
Error	994	16,901.220	17.003		
Dependent: Roll Estimation Error					

Table 4-3. ANOVA for pitch estimation error.

Source	Degree-of-Freedom	Sum of Squares	Mean Square	*F*-Value	*p*-Value
Reference Method	1	503.910	503.910	28.013	0.0001
Subject ID	11	1622.451	147.496	8.200	0.0001
Session	1	4.204	4.204	0.234	0.6289
Error	994	17,880.216	17.988		
Dependent: Pitch Estimation Error					

The mean errors for the two sessions are shown in tables 4-4 and 4-5, for roll and pitch, respectively.

Table 4-4. Session order means for roll estimation error

Session	Count	Mean	Std. Dev.	Std. Error
First	504	5.064	4.375	0.195
Second	504	5.419	4.835	0.215
Dependent: Roll Estimation Error (degrees)				

Table 4-5. Session order means for pitch estimation error.

Session	Count	Mean	Std. Dev.	Std. Error
First	504	6.470	4.401	0.196
Second	504	6.341	4.518	0.201
Dependent: Pitch Estimation Error (degrees)				

4.6.2 Referencing Method Effect

The ANOVA results displayed in tables 4-2 and 4-3 indicate that the null hypothesis (outlined in Section 4.5, Experimental Analysis) can be rejected for the referencing method effect and the test subject effect. The variance attributable to test subject differences is explored in the Section 4.6.3, Test Subject Effect. The variance due to referencing methods is studied here.

4.6.2.1 Roll Axis. The roll axis results are explored first. The high F value and the p value in table 4-2 indicate that H_0 can be rejected and the probability that it is being incorrectly rejected is only 0.01 percent. Thus, the alternative hypothesis—that the differences in the roll estimation error is dependent upon the referencing method—is accepted with a confidence level of 99.99 percent. This significance level is much smaller than the critical cutoff level of 0.01 (or 1 percent) specified for the experiment in Section 4.5, Experimental Analysis.

The mean vehicle roll estimation errors are shown in table 4-6 for gravity-referenced sensors and vehicle-referenced sensors.

Table 4-6. Reference method means for roll estimation error.

Reference Method	Count	Mean	Std. Dev.	Std. Error
Vehicle	504	7.108	5.323	0.237
Gravity	504	3.375	2.695	0.120
Dependent: Roll Estimation Error (degrees)				

It is clear that the gravity-referencing method is facilitating more accurate roll estimations than the vehicle-referencing method for the entire range of vehicle roll angles (i.e., 0 to 20 degrees left and right side slopes). Although the operator's awareness of vehicle attitude is always important, it becomes critical when the vehicle is traversing side slopes of significant angle.

Figure 4-5 displays cell mean (average estimation error for each actual angle) estimation errors plotted against the actual roll angle. The estimation errors associated with gravity-referencing fall within a narrow band across the entire side slope range. The errors are consistent and do not correspond to actual side slope angles. The estimation errors involved with vehicle-referencing increase dramatically as the actual side slope angle increases. The angle estimation errors are nearly as large as the actual side slope angles.

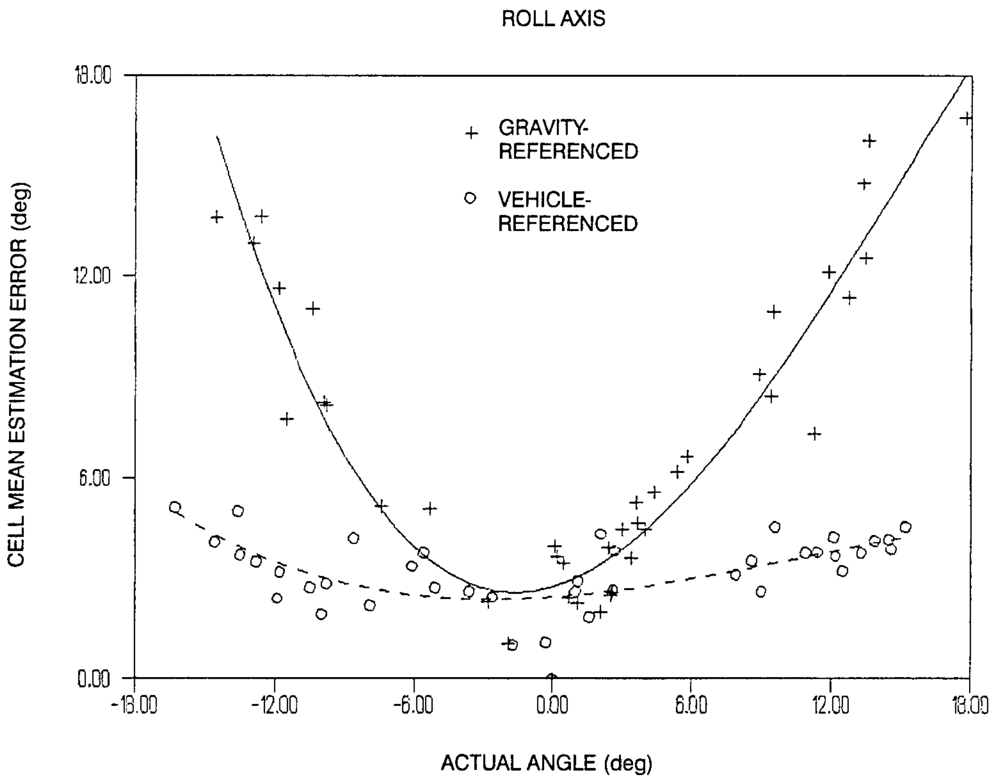

Figure 4-5. Roll angle cell mean estimation errors versus actual angles.

A closer examination of the critical side slope region is made. For this study, the critical region for side slope is defined as greater than 10 degrees. The mean roll estimation errors for gravity- and vehicle-referencing methods for the critical region are shown in table 4-7. The average vehicle-referencing estimation error is 12.4 degrees and the average angle in the critical region is 12.9 degrees. The average gravity-referencing estimation error is 3.9 degrees and the average angle in the critical region is 13.2 degrees.

Table 4-7. Reference method means for critical region roll estimation error.

Reference Method	Count	Mean	Std. Dev.	Std. Error
Vehicle	156	12.445	4.428	0.355
Gravity	240	3.859	2.996	0.193
Dependent: Roll Estimation Error in the Critical Region (degrees)				

The critical region mean estimation error associated with vehicle-referencing is nearly as large as the corresponding mean actual angle. The critical region mean error associated with gravity-referencing is consistent with the mean estimation error for the entire range of data and does not correspond to the actual angle mean for the critical region.

4.6.2.2 Pitch Axis. The ANOVA for the pitch axis data is shown in table 4-3. The high F value and the p value suggest that the null hypothesis, stated in Section 4.5, Experimental Analysis, can be rejected with a confidence level of 99.99 percent. Thus, there is statistically significant evidence that estimation error variance is, at least in part, due to different referencing methods.

The mean vehicle pitch estimation errors are illustrated in table 4-8 for gravity- and vehicle-referenced sensors.

Table 4-8. Reference method means for pitch estimation error.

Reference Method	Count	Mean	Std. Dev.	Std. Error
Vehicle	504	7.112	4.747	0.211
Gravity	504	5.698	4.031	0.180
Dependent: Pitch Estimation Error (degrees)				

The gravity-referencing technique is supplying more orientation cues than the vehicle-referencing method. However, the difference in mean pitch estimation errors is not as dramatic as the difference in mean roll estimation errors.

Figure 4-6 shows pitch cell mean (average estimation error calculated for each actual angle) estimation errors versus the actual angle. Errors associated with both gravity- and vehicle-referencing display the same upward slope, which is especially evident in the positive angle range. The positive slope is attributed to the orientation estimation device, the model vehicle shown in figure 4-2. The model vehicle was suspended in front of the test subject (see figure 4-3). The two-axis inclinometer was mounted just aft of the center line, causing the back of the vehicle to be heavier than the front. Thus, it required less effort for test subjects to rotate the vehicle toward themselves, indicating an up slope, than to rotate the vehicle away from themselves, indicating a down slope. Since the effect is the same for both referencing methods, it does not alter the conclusions drawn. It does, however, enhance the underestimation errors made in the positive angle (up slope) region and diminish the underestimation errors made in the negative angle (down slope) region. Taking this into account, the cell mean errors associated with the

gravity-referencing method are fairly consistent and have only a minor dependence on the actual angles. The cell mean errors associated with the vehicle-referencing method increase proportionally as the actual angles increase. The mean errors at small actual angles drop below the cell mean errors associated with gravity-referencing.

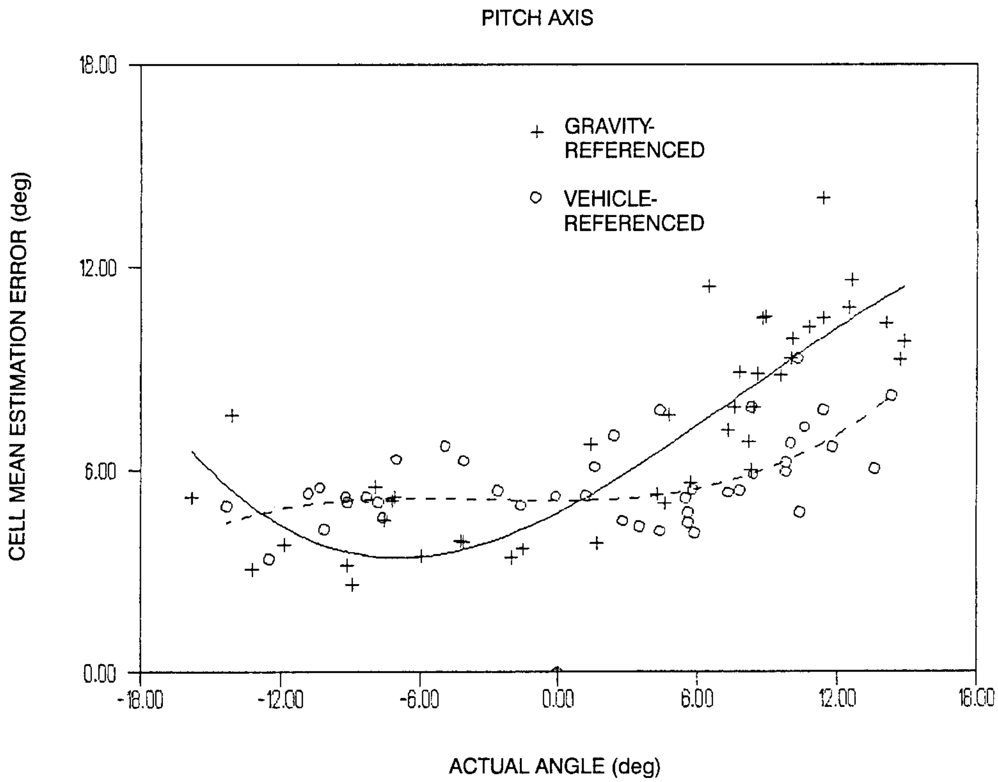

Figure 4-6. Pitch angle cell mean estimation errors versus actual angles.

Finally, the critical region performance is explored. The critical region for pitch analysis is defined as greater than 10 degrees up or down slope. The mean pitch estimation for the critical region is shown in table 4-9 for both referencing methods. The average vehicle-referencing estimation error is 8.9 degrees and the average angle in the critical region is 12.9 degrees. The average gravity-referencing estimation error is 6.1 degrees and the average angle in the critical region is 11.7 degrees.

Table 4-9. Reference method means for critical region pitch estimation error.

Reference Method	Count	Mean	Std. Dev.	Std. Error
Vehicle	156	8.945	5.070	0.406
Gravity	144	6.111	4.104	0.342
Dependent: Pitch Estimation Error in the Critical Region (degrees)				

The mean estimation errors for both gravity- and vehicle-referencing vary minimally from the mean errors involved with the entire angle data range (i.e., 0 to 20 degrees up and down slope). This finding coupled with the cell mean plot information indicates trends in the estimation error data. The angle estimation errors associated with the gravity-referencing method are consistent and nearly independent of the actual angles. The angle estimation errors associated with the vehicle-referencing method are directly proportional to the actual angles. The estimation errors are less than those associated with gravity-referencing for small actual angles and greater for large actual angles.

4.6.3 Test Subject Effect

The variance in performance between test subjects is shown by tables 4-2 and 4-3 to be a statistically significant source of total variance. The goal of this effort is not to investigate operator characteristics that are a factor in vehicle attitude awareness. The analysis of test subject effect does not affect the conclusions of this report and, although it offers an interesting area of study, it will not be pursued in this effort.

4.6.4 Test Subject Confidence Level

On the posttest questionnaire, test operators were asked to declare the level of confidence that they had in the estimates they had just made. The scale ranged from 1 (low) to 5 (high). The underlying assumption to the question is that the more confident operators are in their understanding of the remote vehicle attitude, the more likely they are to take action based on that understanding. If operators' estimations are good and they are confident in them, they will be able to plan successful courses of action. If they are not confident, they will be hesitant to take action even when their estimates are good.

Confidence levels for the gravity-referencing method averaged 3.9 compared with 2.5 for the vehicle-referencing method. Eleven test subjects reported a higher confidence rating for gravity-referencing than for vehicle-referencing. One test subject gave the two methods equal ratings. Results are presented in figure 4-7.

4.6.5 Test Subject Workload Rating

Remote vehicle operators have a heavy workload. The goal of this effort is to improve operators' understanding of vehicle attitude with minimal impact on their workload. When test operators finished each session, they were asked to rate the workload of the task on a scale of 1 (easy) to 5 (difficult). The results are charted in figure 4-8.

The workload ratings averaged 3.5 for the gravity-referencing method and 3.0 for the vehicle-referencing method. These results provide evidence that the gravity-referencing method slightly increases operator workload. The increase, however, is minimal.

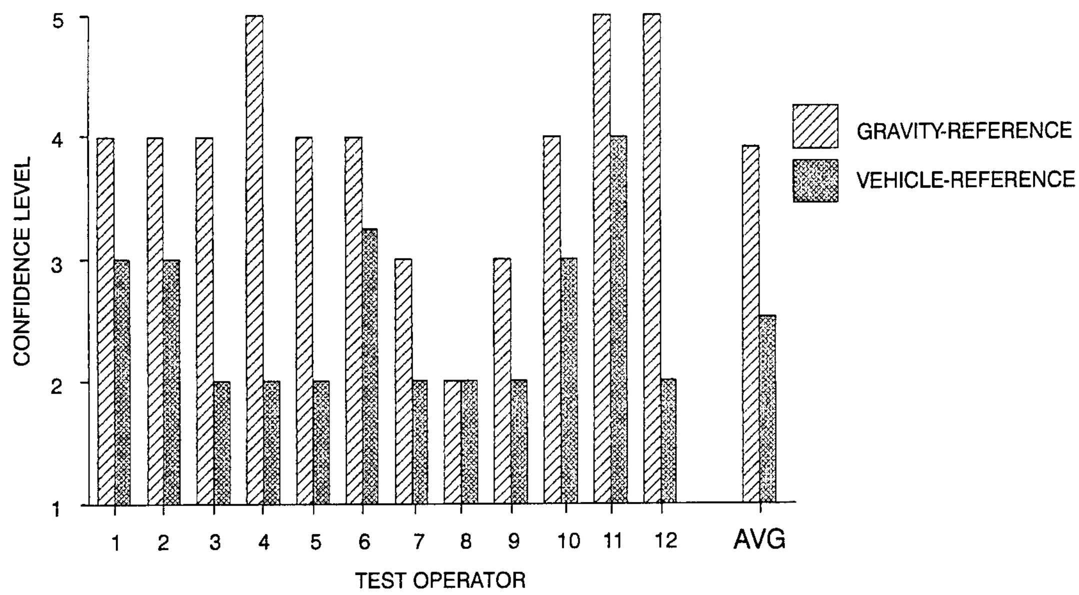

Figure 4-7. Confidence level for pitch and roll estimation.

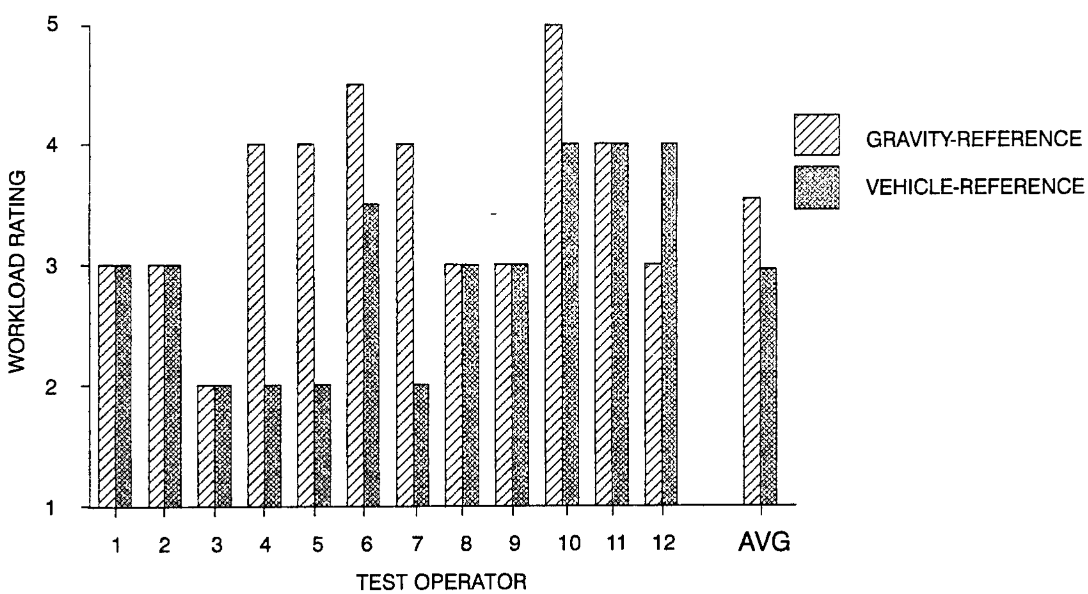

Figure 4-8. Workload rating for gravity- and vehicle-referencing methods.

5. RECOMMENDATIONS AND CONCLUSIONS

5.1 IMPLEMENTATION SUGGESTIONS

The hood of the remote vehicle appeared in the visual work space on the lower third of the video screen. It created a two-dimensional artificial horizon, supplying the operator with remote vehicle attitude information. The results determined in this investigation concerning the effectiveness of gravity-referencing the sensor package are not applicable to a system in which the hood or other significant part of the vehicle front is not visible in the video image.

5.1.1 Graphical Overlay

As described in the previous section, the hood of the remote vehicle served as an artificial horizon. The roll axis of the horizon indicator was a one-to-one angular position mapping of the roll of the vehicle. As a result, the roll angle estimation errors were minimal. The pitch axis of the hood-generated indicator was an angular-to-linear mapping of the pitch of the vehicle. As the vehicle encountered an up slope, the hood filled more than one-third of the video image. When the vehicle went down hill, the hood filled less than one-third of the image. A simple graphic indicator could be overlaid on the edge of the video display to enhance angular position information provided by the linear movement of the hood in the video image.

5.1.2 Three Degree-of-Freedom Platform

The gravity-referencing method can be implemented as a two-degree-of-freedom stand-alone platform, such as the prototype mechanism. This design is especially advantageous for retrofitting teleoperator systems.

Most remote vehicles are equipped with a yaw–pitch (commonly called pan and tilt) mechanism. A pitch–roll referencing platform positioned under a yaw–pitch platform results in a redundant degree-of-freedom in the pitch axis. The two mechanisms can be replaced by one three-degree-of-freedom platform, affording a reduction in cost and complexity. The operator-commanded "head" motions would be combined with the gravity-referencing motions to command the movement of the platform. To achieve a level pan arc, the three-degree-of-freedom platform should be ordered with the roll axis adjacent to the vehicle base, the pitch axis next, and the yaw axis on top.

5.2 SUMMARY

The operator of a teleoperated land vehicle must have a sufficient understanding of the remote vehicle attitude to successfully operate it in an unstructured outdoor environment. The goal of this effort was to develop a human–machine interface that provides sufficient remote vehicle attitude information while minimally impacting operator workload.

The method of gravity-referencing the remote sensor package was implemented. The effectiveness of this method versus vehicle-referencing the sensors was experimentally investigated.

Statistically significant improvement (with a 99.9 percent confidence level) was observed in the operator's understanding of remote vehicle attitude when the sensor package was gravity-referenced compared with when it was vehicle-referenced.

Experimental results showed a significantly higher level of operator confidence in vehicle attitude awareness with the gravity-referencing method. A minimal increase in operator workload was also documented for the method of gravity-referencing.

Gravity-referencing the sensor package presents an added cost in developing or retrofitting a remote vehicle. Statistically significant improvement is not a sufficient reason to implement the gravity-referencing method. The new method must provide an improvement in vehicle attitude awareness of "operational significance" to warrant its implementation. Unlike statistical significance, operational significance is not determined by a defined method or formula; it is a judgment based on the consideration of the data from an operational perspective. Vehicle attitude awareness is most important when the terrain slope magnitudes pose a hazard to the effective operation of the remote vehicle. The effectiveness of the gravity-referencing method was compared with that of the vehicle-referencing method for slopes exceeding 10 degrees (referred to as the critical region).

From the information presented in table 4-7 and accompanying text, the mean roll angle estimation error for the gravity-referencing method is 30 percent of the actual angle. The mean roll angle estimation error for the vehicle-referencing method is 96 percent of the actual angle. Consider, for example, that if an actual side slope of 20 degrees is encountered by a remote vehicle with vehicle-referenced sensors, an operator would estimate the slope as only 0.8 degree. If the same terrain were encountered by a remote vehicle with gravity-referenced sensors, an operator would estimate the slope as 14 degrees. With sensor gravity-referencing implemented, the improvement in the operator's understanding of the vehicle roll angle is operationally significant.

The same comparison is considered for the pitch axis of the remote vehicle. The mean pitch angle estimation error for the gravity-referencing method is 52 percent of the actual angle. The mean pitch angle estimation error for the vehicle-referencing method is 69 percent of the actual angle. These percentages are based on the information in table 4-10 and related analysis. Again, consider that if a remote vehicle with vehicle-referenced sensors encountered an actual side slope of 20 degrees, an operator would estimate the slope as only 5.2 degrees. If the same terrain were encountered by a remote vehicle with gravity-referenced sensors, an operator would estimate the slope as 9.6 degrees. The gravity-referencing method provides an improvement in pitch angle estimation, but the operational significance is not obvious. One idea for enhancing the effectiveness of the gravity-referencing method for pitch angle estimation is presented and discussed in Section 5.1.1, Graphical Overlay. Although the graphical indicator has not been formally tested, informal investigation indicates that the gravity-referencing method coupled with the simple graphical indicator will provide an operationally significant improvement in pitch angle estimation.

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Appendix

EXPERIMENT DOCUMENTS

UNMANNED GROUND VEHICLE HUMAN–MACHINE INTERFACE ATTITUDE AWARENESS STUDY

Explanation of Test Procedures

The experiment described in this document is entitled "UGV Human-Machine Interface Attitude Awareness Study." The experiment is designed to study the effectiveness of two concepts for presenting remote vehicle attitude (pitch and roll) information to the operator. (A remote vehicle is an unmanned mobile platform that is being controlled from some distance away by an operator. An operator uses visual and binaural displays of sensors mounted on the remote vehicle to make operation decisions.)

For the experiment, you will be presented with visual and binaural (audio) displays of sensor data collected from an HMMWV vehicle using two methods. The HMMWV was driven off-road over rough terrain and video, audio, pitch, and roll data were recorded. You will not be directly operating or teleoperating (remote controlling) the HMMWV vehicle. The video you will be viewing and audio you will be hearing were prerecorded. There are no vehicle safety issues to be concerned with during the experiment.

You will participate in two test sessions, each session will feature a different method of presenting remote vehicle attitude information via the video and audio displays. Each test session will consist of 14 prerecorded driving scenarios, each 45 seconds in length. At three random points during each 45-second scenario, the video and audio will be stopped, and you will make an estimate of the orientation with respect to gravity, (pitch and roll angles) of the HMMWV vehicle. You will express your estimate by positioning a model vehicle in the same orientation as the observed HMMWV vehicle, then pressing a button.

There will be a brief practice session during which you will have the opportunity to become familiar with the test equipment and procedures. The practice session will take approximately ten minutes. The test sessions will require between 20 and 25 minutes each.

Your participation is important and greatly appreciated! The information derived from this experiment will assist engineers and scientists in designing and building better remotely operated vehicles.

Please perform as well as you can. Remember, we are not analyzing your performance to compare with that of other test subjects; we are interested only in comparing design features of the hardware used to collect and display vehicle attitude information.

UNMANNED GROUND VEHICLE HUMAN–MACHINE INTERFACE ATTITUDE AWARENESS STUDY

Pretest Questionnaire

Name:

Phone (work): Age: Sex:
Occupation:

1. Are you licensed to drive a motor vehicle?
   If yes, how many years?

2. Are you familiar with an HMMWV as a
   - driver?
   - passenger?
   - direct observer?
   - other (please list)?

3. Do you have problems with your vision (that have not been corrected with aids)?
   If yes, please explain:

4. Do you have problems with your hearing (that have not been corrected with aids)?
   If yes, please explain:

5. How susceptible to motion sickness are you? (circle one)
   - Extremely
   - Very
   - Moderately
   - Minimally
   - Not at all

6. What is your off-road driving experience? (circle one)

none		
minimal: driver	passenger	both
moderate: driver	passenge	both
substantial: driver	passenger	both

UNMANNED GROUND VEHICLE HUMAN–MACHINE INTERFACE ATTITUDE AWARENESS STUDY

Posttest Questionnaire

1. Rate your confidence level for the vehicle orientation estimates you just made.

LOW (guess)				HIGH (very confident)
1	2	3	4	5

2. Did you like this view from the vehicle?

NOT-AT-ALL				VERY MUCH
1	2	3	4	5

3. Did you experience any physical ill effects (eye strain, nausea, headaches, etc.)? If so, please list them and rate the severity. Did any of these symptoms impair your ability to do the task?

SYMPTOM	ILL EFFECT			IMPAIRED ABILITY		
	noticeable		severe	no	slightly	yes
__________	1	2	3	A	B	C
__________	1	2	3	A	B	C
__________	1	2	3	A	B	C

4. Rate the task workload (level of calculation, determination, cognitive effort) of making the orientation estimates.

LIGHT (very easy)				HEAVY (very hard)
1	2	3	4	5

5. Please list your comments and observation:

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13. ABSTRACT *(Maximum 200 words)*

The operator of a teleoperated land vehicle must have a sufficient understanding of the attitude of a remote vehicle to successfully operate it in an unstructured outdoor environment. The goal of this effort was to develop a human–machine interface that provides sufficient remote vehicle attitude information while minimally impacting operator workload.

Referencing the remote video sensors to the earth's gravitational field was proposed as a means of providing vehicle attitude information to the operator. The hood of the remote vehicle appeared in the video image and served as a two-dimensional artificial horizon, providing the operator with vehicle pitch and roll information in a natural, nonintrusive manner.

The effectiveness of gravity-referencing the sensors was experimentally tested and compared with vehicle-referencing the sensors on the same teleoperator system. Experimental results confirmed that gravity-referencing the sensors provided the operator with improved vehicle attitude information. In addition, results showed a significantly higher level of operator confidence in vehicle attitude awareness with the gravity-referencing method. A minimal increase in operator workload was also documented for the method of gravity-referencing.

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